LADDER FILTER, ANALOG EQUALIZER AND SIGNAL READOUT SYSTEM

BACKGROUND OF THE INVENTION

The present invention relates to an analog filter for use in a signal readout system for a magnetic or magneto-optical disk, for example.

As magnetic/magneto-optical disk technologies have been remarkably developed in recent years, it has become increasingly necessary to further improve the signal processing technology applicable to reading signals therefrom.

Figure **12** illustrates a known magnetic/magneto-optical disk signal readout system. A signal, read out from a disk **80**, is amplified by an amplifier **81** first, and then passed through an analog filter **82** so as to have its noise reduced and its gain boosted. As used herein, "gain boosting" means a signal processing technique of sharpening the edges of a signal by boosting the high-frequency components thereof. Then, the analog output signal of the analog filter **82** is converted into a digital signal by a data slicer **83**. A recent system sometimes decodes an A/D converted signal by a maximum likelihood method. Even in such a system, however, the performance required for its analog filter is much the same.

Figure **13** illustrates ordinary frequency characteristics

of an analog filter for use in a signal readout system for a magnetic or magneto-optical disk. In constructing a signal readout system for a magnetic or magneto-optical disk, its analog filter is usually designed using a Bessel filter or an equal-ripple filter so as to sharpen the signal edges and so as not to distort the signal waveform. This is because should the analog filter distort the signal waveform, the locations of the signal edges displace, thus possibly causing errors in digitizing a signal using a data slicer.

Accordingly, an analog filter is designed such that its transfer function **H(s)** is given by the following Equation (1)

$$H(s)=(1-s^2)/D(s)=(1+\omega^2)/D(j\omega) \qquad (1)$$

where s is a Laplace variable and D(s) is a function representing the denominator of the transfer function of the analog filter. In this case, the numerator of the transfer function **H(s)** has no imaginary part and therefore does not affect the phase characteristic of the analog filter. In addition, since the high-frequency gain is boosted by the term ω^2, the gain-boosted characteristic such as that illustrated in Figure **13** is obtained.

A filter with the gain-boosted characteristic such as that illustrated in Figure **13** is implementable by a cascade of biquadratic filters such as those illustrated in Figure **14**. A biquadratic filter usually has quadratic poles. However, if two such filters are cascaded as shown in Figure **14**, then

quadratic poles and first zeroes can be easily made in their transfer function. That is to say, the transfer function of each of the biquadratic filters shown in Figure **14** is given by the following Equation (2):

$$H1(s)=(gm1 \cdot gm2+sC2 \cdot gm1x)/(gm2^2+sC2 \cdot gm3+s^2C1C2) \qquad (2)$$

Thus, the transfer function **H(s)** of the cascade of the two biquadratic filters shown in Figure **14** is given by the following Equation (3):

$$H(s)=\{(gm1 \cdot gm2)^2-s^2\}/(gm2^2+sC2 \cdot gm3+s^2C1C2)^2 \qquad (3)$$

In this manner, a transfer function having no imaginary part in its numerator and yet having the term ω^2 can be obtained, thus easily realizing the gain-boosted characteristic.

A filter network implemented as a cascade of biquadratic filters, however, has its characteristic easily affected by the variation of its components.

Figure **15** illustrates a Laplace plane representing the characteristic of an analog filter. The characteristic of an analog filter can usually be represented using a collection of poles and zeroes on a Laplace plane. In the following description, however, the characteristic of an analog filter will be regarded as a consisting of poles for the sake of simplicity.

As shown in Figure **15**, a frequency vector is represented as $s=j\omega$ and its end point rises along the imaginary axis of the Laplace plane as the frequency increases. On the other

hand, the frequency characteristic of an analog filter is given by

$$H(s) = \prod_{k=1}^{n} 1/(s - sk)$$

where sk is a vector representing the position of each pole on the Laplace plane. Thus, a frequency gain is an inverse of the product of the vector $(s - sk)$. That is to say, the frequency characteristic of an analog filter is more likely to be affected by a relatively short vector $(s - sk)$. In other words, the frequency characteristic of the filter is affected most by the position of a pole **Sk** that is closest to the imaginary axis. Also, the position of a pole displaces on the Laplace plane due to the characteristic variations of filter components.

In an analog filter network implemented as a cascade of biquadratic filters, a pair of poles is realized by each of these biquadratic filters. Thus, as shown in Figure **16(a)**, the characteristic variation of a biquadratic filter **BQ1** realizing the pairs of poles closest to the imaginary axis is a key factor of the variable characteristic of the analog filter network. Accordingly, the frequency characteristic of such a cascade of biquadratic filters is easily affected by the characteristic variation of its components.

An analog filter may also be implemented as a ladder filter. In a ladder filter, capacitors and inductors are connected together in a ladder shape and its input and output

are terminated with resistors. In an LSI, an inductor is usually non-implementable, and therefore is replaced with an equivalent circuit including voltage-controlled current sources and capacitors, thereby constructing a ladder filter. In such a case, the ladder filter is implemented with plural biquadratic filters all coupled together.

Accordingly, in a ladder filter, the positions of all the poles are affected by the characteristic variations of its components. Thus, as shown in Figure **16(b)**, if the characteristics of its components vary, then the positions of all the poles change. However, the magnitude of the displacement itself is much smaller compared to the cascade of biquadratic filters. Also, the displacement of the poles closest to the imaginary axis, which affects the frequency characteristic most seriously, becomes relatively small, too. Accordingly, the ladder filter does not have its characteristic affected by the characteristic variations of its components so much as the cascade of biquadratic filters.

However, the ladder filter is essentially a filter network of passive components. Thus, it has been widely believed that it is difficult to increase its gain to 1/2 or more or to realize the gain-boosted characteristic as illustrated in Figure **13**.

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to provide an analog filter exhibiting a gain-boosted characteristic, which is almost consistent even against the characteristic variations of its components.

Specifically, an inventive ladder filter includes multiple inductor sections, each being implemented by an equivalent circuit including voltage-controlled current sources and capacitors. A signal input to the ladder filter is provided to at least one of the voltage-controlled current sources by way of gain adjusting means. A gain obtained by the gain adjusting means is set to such a value as realizing a desired transfer function for the ladder filter.

In the inventive ladder filter, which exhibits a highly consistent filter characteristic even against the characteristic variations of its components, a signal input to the ladder filter is provided to at least one of the voltage-controlled current sources in the inductor sections by way of the gain adjusting means. As a result, even a transfer function, which has been hard to realize in a conventional ladder filter, is also realizable. For example, by setting the ratio of the gains obtained by the gain adjusting means to such a value that the transfer function of the ladder filter has a numerator consisting of only a term that is an even-numbered power of s, e.g., $(1+s^2)$, the ladder filter can vary only its gain

characteristic while keeping its phase characteristic substantially constant.

In one embodiment of the present invention, a ratio of the gains obtained by the gain adjusting means is preferably set to such a value as making the ladder filter exhibit a desired gain-boosted characteristic independent of its phase characteristic.

In another embodiment, the inventive ladder filter may further include a first signal input terminal provided for a filtering process and a second signal input terminal provided separately from the first signal input terminal. The gain adjusting means preferably receives a signal that has been input to the second signal input terminal.

In this particular embodiment, the inventive ladder filter preferably further includes a variable-gain amplifier provided at a stage preceding the second signal input terminal.

In still another embodiment, a variable gain is preferably obtained by the gain adjusting means.

An inventive analog equalizer includes: a ladder filter including multiple inductor sections, each being implemented by an equivalent circuit including voltage-controlled current sources and capacitors; means for detecting an error between an output signal of the ladder filter and a reference signal; and means for changing a filter characteristic of the ladder

filter by reference to the error that has been detected by the detecting means. A signal input to the ladder filter is provided to at least one of the voltage-controlled current sources by way of gain adjusting means, which obtains a variable gain. The changing means changes the gain, obtained by the gain adjusting means of the ladder filter, based on the error that has been detected by the detecting means.

An inventive signal readout system includes the analog equalizer of the present invention, reads out a signal from a recording medium such as a magnetic or magneto-optical disk and filters the signal using the analog equalizer.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure **1** illustrates a configuration for a ladder filter according to a first embodiment of the present invention.

Figure **2** is a circuit diagram illustrating a prototype of the ladder filter.

Figure **3** is an equivalent circuit diagram of an inductor section for the ladder filter.

Figure **4** illustrates a ladder filter according to a second embodiment of the present invention.

Figure **5** illustrates a configuration for a ladder filter according to a third embodiment of the present invention.

Figure **6** illustrates a configuration for an analog equalizer according to the third embodiment.

Figure 7 illustrates a determinant representing the numerator of a transfer function for the filter shown in Figure 6.

Figure 8 illustrates a modification of the determinant shown in Figure 7.

Figure 9 illustrates a configuration for a prior art equalizer including a digital circuit.

Figure 10 illustrates a configuration for another conventional analog equalizer.

Figure 11 is a block diagram illustrating a configuration for a magnetic or magnet-optical disk signal readout system including the analog equalizer according to the third embodiment.

Figure 12 is a block diagram illustrating a configuration for a known magnetic or magneto-optical disk signal readout system.

Figure 13 illustrates an ordinary frequency characteristic of an analog filter for use in a signal readout system.

Figure 14 illustrates exemplary biquadratic filters.

Figure 15 illustrates a Laplace plane representing the characteristic of an analog filter.

Figure 16(a) illustrates the characteristic of a filter network implemented as a cascade of biquadratic filters; and

Figure 16(b) illustrates the characteristic of a ladder filter.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

EMBODIMENT 1

Figure **1** illustrates a configuration for a ladder filter **1** according to a first embodiment of the present invention. The ladder filter **1** shown in Figure **1** is a 7^{th}-order equal-ripple filter and realizes a gain-boosted characteristic independent of its phase characteristic.

Figure **2** is a circuit diagram illustrating a prototype for the ladder filter **1** and Figure **3** illustrates an equivalent circuit of an inductor section for the ladder filter **1**. As shown in Figure **3**, the equivalent circuit includes voltage-controlled current sources **51a** and **51b** and capacitors **52a** and **52b**. That is to say, the ladder filter **1** shown in Figure **1** includes multiple inductor sections, each of which is implemented by the equivalent circuit shown in Figure **3**.

As shown in Figure **1**, the ladder filter **1** includes ordinary signal input terminal **IN1**, signal output terminal **OUT**, voltage-controlled current sources **11a** through **11g** and capacitors **C1** through **C7**. The ladder filter **1** shown in Figure **1** is characterized by further including a second signal input terminal **IN2** in addition to the signal input terminal **IN1**. And the filter **1** is so constructed as providing a signal **Vin**, which has been input to the signal input terminal **IN2**, to the first through third voltage-controlled current sources **11a** through **11c** via constant-ratio gain calculators **15a** through

15c (which are exemplary gain adjusting means), respectively.

Without the second signal input terminal **IN2**, the ladder filter 1 shown in Figure **1** will have a transfer function of a 7^{th}-order equal-ripple filter. The denominator of this transfer function is determined by the feedback characteristic of the circuit. However, even if the number of signal input terminals is increased, the feedback characteristic of the circuit does not change. Accordingly, the denominator of the transfer function does not change whether the second signal input terminal **IN2** is added or not. That is to say, only the numerator term of the transfer function of the ladder filter is affected by the addition of the second signal input terminal **IN2**.

Thus, if the input signal **Vin** is provided to any of the voltage-controlled current sources **11a** through **11g** separately from the ordinarily input signal with its input gain appropriately controlled, then the transfer function of the ladder filter will have a freely modifiable numerator. As a result, a filter with any of various response characteristics will be obtainable in that case. That is to say, by taking advantage of a technical concept like this, a ladder filter according to this embodiment realizes a desired gain-boosted characteristic independent of its phase characteristic.

Unless the second signal input terminal **IN2** is provided, the ladder filter 1 shown in Figure 1 may have a transfer

function **H(s)** given by the following Equation (4):

$$H(s) = 0.5/Hr(s) = 0.5/(1.000000000s^7 + 5.233611506s^6 + 19.69755040s^5 + 45.91809198s^4 + 76.50647398s^3 + 84.06826807s^2 + 57.09056406s + 17.97359538) \quad (4)$$

It should be noted that the cutoff frequency is normalized at 1 Hz for the sake of simplicity and

R=1

gm=1

C1=2.28476155

C2=0.874875016

C3=0.6653020972

C4=0.208510173

C5 (=L1)=1.06718322

C6 (=L2)=0.7521265315 and

C7 (=L3)=0.4999563649

Since the transconductance **gm** is one, the capacitance values of the capacitors **C5** through **C7** are equal to those of **L1** through **L3**, respectively. If the cutoff frequency has changed, then the transfer function may be transformed in accordance with a known frequency scaling formula as in an ordinary filter design process.

Supposing the gains obtained by the respective constant-ratio gain calculators **15a** through **15c** are denoted by **gin**, **gm1** and **gm2**, the transfer function of the ladder filter 1 shown in Figure 1 will have a numerator **Hn(s)** given by the following

Equation (5):

$$Hn(s) = 1.219129594gm2s^2 + (1.142380774gm1 + 0.5335916099gm2)s + (0.5gm2 + 0.5gm1 + 0.5gin + 0.5) \quad (5)$$

If the 0^{th} and 1^{st}-order terms of the numerator **Hn(s)** are 0.5 and 0, respectively, then the gain-boosted characteristic is realized and the circuit shown in Figure **1** will be a gain booster. Thus, the ladder filter **1** shown in Figure **1** can exhibit the gain-boosted characteristic when the respective gains **gin**, **gm1** and **gm2** meet the relationships represented by the following Equations (6):

$$1.142380774gm1 + 0.5335916099gm2 = 0$$
$$0.5gm2 + 0.5gm1 + 0.5gin = 0 \quad (6)$$

If these Equations are solved, then

$$gm2 = -2.140927168gm1$$
$$gin = 1.140927168gm1$$
$$\therefore Hn(s) = -2.61gm1s^2 + 0.5 \quad (7)$$

Thus, the ladder filter **1** shown in Figure **1** has a transfer function **H(s)** given by the following Equation (8):

$$H(s) = (-2.61gm1s^2 + 0.5) / Hr(s) \quad (8)$$

As can be seen from this transfer function **H(s)** equation, a desired gain-boosted characteristic is attainable by setting the gain **gm1** obtained by the constant-ratio gain calculator **15b** to an appropriate value and the boosted gain is changeable by adjusting the gain **gm1**.

By providing an additional input signal to a voltage-

controlled current source separately from an ordinarily input signal and by appropriately controlling the gain ratio in this manner, this embodiment realizes a desired gain characteristic without disturbing its phase characteristic.

The ladder filter **1** shown in Figure **1** is also characterized in that the signal input to the first voltage-controlled current source **11a** is not Vin · gin but (Vin + Vin · gin). If Vin · gin is simply input, then the transfer function **H(s)** given by Equation (8) is not realizable.

In other words, to make only the gain-boosted characteristic controllable independently, (Vin + Vin · gin) should be input to the first voltage-controlled current source **11a**. This is because if Vin · gin is input to the first voltage-controlled current source **11a**, then it is impossible to control only the gain-boosted characteristic independently.

EMBODIMENT 2

Figure **4** illustrates a ladder filter according to a second embodiment of the present invention. As shown in Figure **4**, the ladder filter according to this embodiment further includes first and second variable-gain amplifiers **21a** and **21b** at a stage preceding the input terminals **IN1** and **IN2** of the ladder filter **1** of the first embodiment.

By adjusting the gain of the second variable-gain amplifier **21b**, the intensity of the signal input to the second

signal input terminal **IN2** is controllable independent of the signal input to the first signal input terminal **IN1**. Accordingly, as can be seen from the transfer function **H(s)** equation (8), the boosted gain of the ladder filter **1** is easily changeable. That is to say, by dividing the variable-gain amplifier preceding the input stage into two, the boosted gain of the ladder filter is controllable independent of the gain control for an ordinarily input signal.

In addition, since the gains are controlled using the variable-gain amplifiers **21a** and **21b**, the boosted gain can be changed more smoothly compared to using a switch, for example.

EMBODIMENT 3

Figure **5** illustrates a configuration for a ladder filter **3** that realizes a desired transfer function according to a third embodiment of the present invention. In Figure **5**, the same components as the counterparts shown in Figure **1** are identified by the same reference numerals and the description thereof will be omitted herein.

The ladder filter **3** shown in Figure **5** is characterized in that the signal received at the second signal input terminal **IN2** is provided to all of the voltage-controlled current sources **11a** through **11g** via the constant-ratio gain calculators **31a** through **31g** (which are exemplary gain adjusting means), respectively. The filter **3** is also characterized in

that the gains obtained by the constant-ratio gain calculators **31a** through **31g** are controllable through respective gain control terminals **CN1** through **CN7**.

As described in the first embodiment, in a ladder filter with multiple inductors, each implemented as an equivalent circuit consisting of voltage-controlled current sources and capacitors, the input signal **Vin** is provided to any of the voltage-controlled current sources **11a** through **11g** separately from the ordinarily input signal. And its input gain is adjusted appropriately, thereby freely controlling the numerator of its transfer function. That is to say, a desired transfer function is realizable for the ladder filter **3** shown in Figure **5** by controlling the gains of the constant-ratio gain calculators **31a** through **31g** through the gain control terminals **CN1** through **CN7**, respectively.

The ladder filter **3** shown in Figure **5** is applicable to an equalizer, for example. By using the filter shown in Figure **5**, a downsized equalizer with more consistent characteristic is obtained.

Figure **6** illustrates a configuration for an analog equalizer including the ladder filter **3** shown in Figure **5** according to the third embodiment. As shown in Figure **6**, the equalizer further includes an error detector **31** and a filter characteristic changer **32**. Receiving the output signal **Vout** of the ladder filter **3** and a reference signal **Vref**, the error

detector **31** detects and outputs an error between these signals. In response to the output signal of the error detector **31**, the filter characteristic changer **32** changes the response characteristic (filter characteristic) of the ladder filter **3**.

The ladder filter **3** may have the numerator **Hn(s)** of its transfer function represented by a determinant shown in Figure **7**. In Figure **7**, the determinant includes three matrices **Gm**, **A** and **S**. The matrix **Gm** represents the gain settings **gm0** through **gm6** of the respective constant-ratio gain calculators **31a** through **31g**. The matrix **A** represents the response of the filter **3**. And the matrix **S** consists of powers of a Laplace variable **s**.

A determinant shown in Figure **8** is obtained from the determinant shown in Figure **7**. In Figure **8**, **K** is a matrix representing the 0^{th} through 6^{th}-order coefficient values **K0** through **K6** of **Hn(s)**. Accordingly, the gain **Gm** that should be obtained to define a numerator polynomial of **Hn(s)** with respect to an arbitrary coefficient value **K** is given by

$$\bar{Gm} = (A^T)^{-1} \times K$$

In the equalizer shown in Figure **6**, the filter characteristic changer **32** includes: a filter characteristic determiner **33** for determining the coefficient **K** for the filter characteristic; and a coefficient transformer **34** for determining the gain coefficient **Gm** of the ladder filter **3** by the value of the coefficient **K**. In this way, the gain coefficient **Gm**

can be determined such that the ladder filter **3** shows arbitrary response.

The respective elements of the matrix **A** can be obtained in the following manner. For example, the elements a_{66}, a_{65}, a_{64}, a_{63}, a_{62}, a_{61} and a_{60} on the first row of the matrix **A** are coefficients for respective orders in the numerator of the transfer function when the input signal **Vin** is provided only to the seventh voltage-controlled current source **11g** via the constant-ratio gain calculator **31g** in the filter shown in Figure **5**. Accordingly, in that case, the input signal **Vin** should not be input through the ordinary signal input terminal **IN1**, the gains of the first through sixth constant-ratio gain calculators **31a** through **31f** should be set to zero and only the gain of the seventh constant-ratio gain calculator **31g** should be set to one. Then, the transfer function of the ladder filter **3** should be derived from the output signal **Vout** in that case. And the coefficients for respective orders in its numerator may be regarded as the elements a_{66}, a_{65}, a_{64}, a_{63}, a_{62}, a_{61} and a_{60} on the first row of the matrix **A**.

In the same way, the elements a_{55}, a_{54}, a_{53}, a_{52}, a_{51} and a_{50} on the second row of the matrix **A** are coefficients for respective orders in the numerator of the transfer function when the input signal **Vin** is input only to the sixth voltage-controlled current source **11f** via the constant-ratio gain calculator **31f**. Accordingly, in that case, the input signal

Vin should not be input through the ordinary signal input terminal **IN1**, the gains of the first through fifth and seventh constant-ratio gain calculators **31a** through **31e** and **31g** should be set to zero and only the gain of the sixth constant-ratio gain calculator **31f** should be set to one. Then, the transfer function of the ladder filter **3** should be derived from the output signal **Vout** in that case. And the coefficients for respective orders in its numerator may be regarded as the elements a_{55}, a_{54}, a_{53}, a_{52}, a_{51} and a_{50} on the second row of the matrix **A**. The other matrix elements from the third row on can be obtained in a similar manner.

Figure **9** illustrates, as a comparative example, a configuration for a prior art equalizer circuit including a digital circuit. As shown in Figure **9**, the prior art equalizer circuit additionally needs an A/D converter **66** and a digital equalizer **67**, thus dissipating more power than the analog equalizer of the present invention.

Figure **10** illustrates, as another comparative example, a configuration for another analog equalizer circuit (see, for example, "A 160 MHz Analog Front-End IC for EPR-IV PRML Magnetic Storage Read Channels", P. Pai, A. Brewster and A. A. Abidi, IEEE J. of Solid-State Circuits, pp. 1803-1816, November, 1996). In the analog equalizer circuit shown in Figure **10**, an analog differentiator is cascaded with a conventional filter circuit. However, it is usually difficult to design a

differentiator using analog components.

In contrast, according to this embodiment, an analog equalizer circuit is implementable just by providing another input terminal for the ladder filter separately from an ordinary signal input terminal and by inputting a signal through this additional input terminal to the respective voltage-controlled current sources by way of the gain converters. Thus, there is no need to add the differentiator or the like circuit hard to implement with analog components. Furthermore, according to this embodiment, an equalizer circuit can be constructed using the ladder filter with the consistent characteristic. As a result, the characteristic of the equalizer circuit can be further stabilized.

The analog equalizer according to this embodiment is easily applicable to a signal readout system for use in magnetic or magneto-optical recording by a partial response maximum likelihood (PRML) method, in which Viterbi decoding and partial response (PR) equivalent transformation are used in combination.

The PRML method is a promising signal reading method, because the SNR of the read signal can be improved compared to conventional magnetic recording techniques using a data slicer. Accordingly, a magnetic or magneto-optical disk signal readout system including the analog equalizer of the present invention can have its digital circuit section downsized

compared to the conventional signal readout system including the digital equalizer. Thus, the present invention contributes to reduction in power dissipated and circuit size.

Figure **11** illustrates a configuration for a magnetic or magnet-optical disk signal readout system including the analog equalizer according to the third embodiment. As shown in Figure **11**, the system includes an analog equalizer **40** with the configuration shown in Figure **9**. The analog equalizer **40** can function by itself not only as an equalizer but also as a low-pass filter as well.

In the conventional signal readout system for use in PRML magnetic or magneto-optical recording, the equalizer often includes a digital filter. This is because no analog equalizers, qualified for the signal readout system, have been available so far. In contrast, the analog equalizer according to this embodiment uses the ladder filter with a low sensitivity as a basic circuit component and needs no differentiator that is hard to implement using analog components. Thus, compared to the conventional analog equalizer, the inventive analog equalizer attains much higher precision and requires much less area and power. Furthermore, an analog equalizer can reduce power dissipation more easily than a digital equalizer generally speaking.

Accordingly, a signal readout system including the analog equalizer of the present invention is much more advan-

tageous in precision, area and power dissipation. It should be noted that the same effects are also attainable by applying the inventive analog equalizer to any system for reading out a signal from a recording medium other than a magnetic or magneto-optical disk.

As described above, the inventive ladder filter exhibits a filter characteristic highly consistent even against the characteristic variations of its components and provides its input signal to at least one of the voltage-controlled current sources for inductor sections via gain adjusting means. As a result, even a transfer function that has been hard to realize in the conventional filters is realizable. For example, by setting the ratio of the gains obtained by the gain adjusting means to such a value that the transfer function of the ladder filter has a numerator $(1+s^2)$, a desired gain-boosted characteristic is realizable independent of its phase characteristic.

In addition, by using such a filter, a downsized analog equalizer with stabilized characteristics can be obtained. Furthermore, a signal readout system including an analog equalizer like this is much more advantageous in precision, area and power dissipation.